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ADVANCED CONTROL FILTERING AND PREDICTION FOR PHASED ARRAYS IN DIRECTED ENERGY SYSTEMS

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Final Report

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14. ABSTRACT

UCLA research under this project has developed advanced methods for control, filtering, prediction and system identification in adaptive optics, laser beam pointing and target tracking. These methods can achieve significant improvements in on-target Strehl ratios and tracking jitter for phased-array high energy laser systems.

15. SUBJECT TERMS
Optics, Strehl, jitter, phased-array, high energy laser

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1.0 SUMMARY

University of California, Los Angeles (UCLA) research under this project has developed advanced methods for control, filtering, prediction and system identification in adaptive optics, laser beam pointing and target tracking. These methods can achieve significant improvements in on-target Strehl ratios and tracking jitter for phased-array high energy laser systems. The main technical contribution of the research under this grant is a method for phase unwrapping, prediction and correction in phased arrays. The new method combines phase unwrapping logic with Kalman filtering and prediction in a feedback control loop. Analysis and simulation have shown that the new method can track and correct optical phase with slowly varying phase velocity and that the method is reasonably robust to sensor noise. Following is a detailed discussion of this method and representative simulation results.

2.0 INTRODUCTION

Under this grant, research at UCLA has developed advanced methods for control, filtering, prediction and system identification in adaptive optics, laser beam pointing and target tracking. These methods can achieve significant improvements in on-target Strehl ratios and tracking jitter for phased-array high energy laser systems.

A primary objective of the proposed research is to develop novel methods for wavefront prediction and correction and reduction of tilt jitter, such as two methods that increase bandwidths of wavefront correction and jitter control. An equally important objective will be to develop analysis and simulation tools to evaluate closed-loop performance of phased array systems with a variety of control system designs and subject to realistic disturbances, measurement and reconstruction errors and system latencies.

The main technical contribution of the research under this grant is a method for phase unwrapping, prediction and correction in phased arrays. The new method combines phase unwrapping logic with Kalman filtering and prediction in a feedback control loop. Analysis and simulation have shown that the new method can track and correct optical phase with slowly varying phase velocity and that the method is reasonably robust to sensor noise. Following is a detailed discussion of this method and representative simulation results.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Control and Filtering Methods

The primary methods used to design the predictor and feedback control loop are the following:

- Kalman filtering and prediction
- Feedback control
- Phase Unwrapping

3.2 Assumptions

It is assumed that a possibly noisy measurement of wrapped optical phase is available to the digital feedback control system.

3.3 Design, Analysis and Simulation Procedures

The research procedure consists of designing the predictor, phase unwrapping logic and feedback control law, analyzing the closed-loop system theoretically to guarantee stability and simulating the closed-loop system in SIMULINK.

4.0 RESULTS AND DISCUSSION

4.1 Feedback Control of Phase Ramp with Kalman Prediction from Wrapped Phase Measurements

This discussion summarizes results from a study of mod 4π phase measurement and the effects of sensor noise and velocity variation on the estimation, prediction and control of a phase ramp. Figure 1 shows a closed-loop system with two rates, one rate for simulation and the second rate for the controller. The mirror is represented by an integrator, so that the control command is a rate command to the mirror. This model assumes that the position of the mirror can be measured and used by the control loop, although this measurement probably is not necessary.

4.2 Simulation Model

There are three differences between the current SIMULINK model and the previous models: The measurement is mod 4π in the current model instead of mod 2π in the previous models, white sensor noise is added to the phase measurement before the 4π block, and the current model provides for a band-limited disturbance to be added to the phase velocity. The results discussed here were generated with only the white sensor noise. The study with velocity disturbance is in progress and will be reported later.

The controller consists of the blue blocks in Figure 1. The open-loop phase is the signal to be predicted and corrected. The Kalman predictor and unwrapping function take the delayed closed-loop phase error (mod 4π) as the only input, and generate a prediction of the open-loop phase. This prediction is subtracted from the true open-loop phase to form the closed-loop phase error.

The sample-and-hold rate for control is defined to be *tcontr* = 1. The simulation rate, denoted by *tsim*, normally is some fraction of *tcontr*. For the simulation results in the subsequent figures, *tsim* = 1/40, and the measurement delay is either one control sample interval (= 40 *tsim*) or two control samples (= 40 *tsim*). A few simulations with *tsim* = 1/200 yielded essentially identical results to those presented here, so *tsim* = 1/40 was used for most of the numerous simulations of which the results here are representative.

4.3 Phase Velocity Range for Stable Tracking

The most important parameter is the ratio of the phase velocity *vr* to the control sample interval. Since that sample interval is 1 in this model, the important ratio is *vr*. For the mod 4π phase measurement, the current controller can track the phase and produce a reliably stable closed-loop error for phase velocities with magnitude up to $0.75\times 2\pi$ / control sample period. The closed-loop track loop is stable for somewhat larger velocities for sufficiently small sensor noise and some values of the initial phase. This suggests that further refinement of the Kalman predictor and control loop might produce a stable track loop for velocities somewhat larger than $0.75\times 2\pi$, but possibly not.

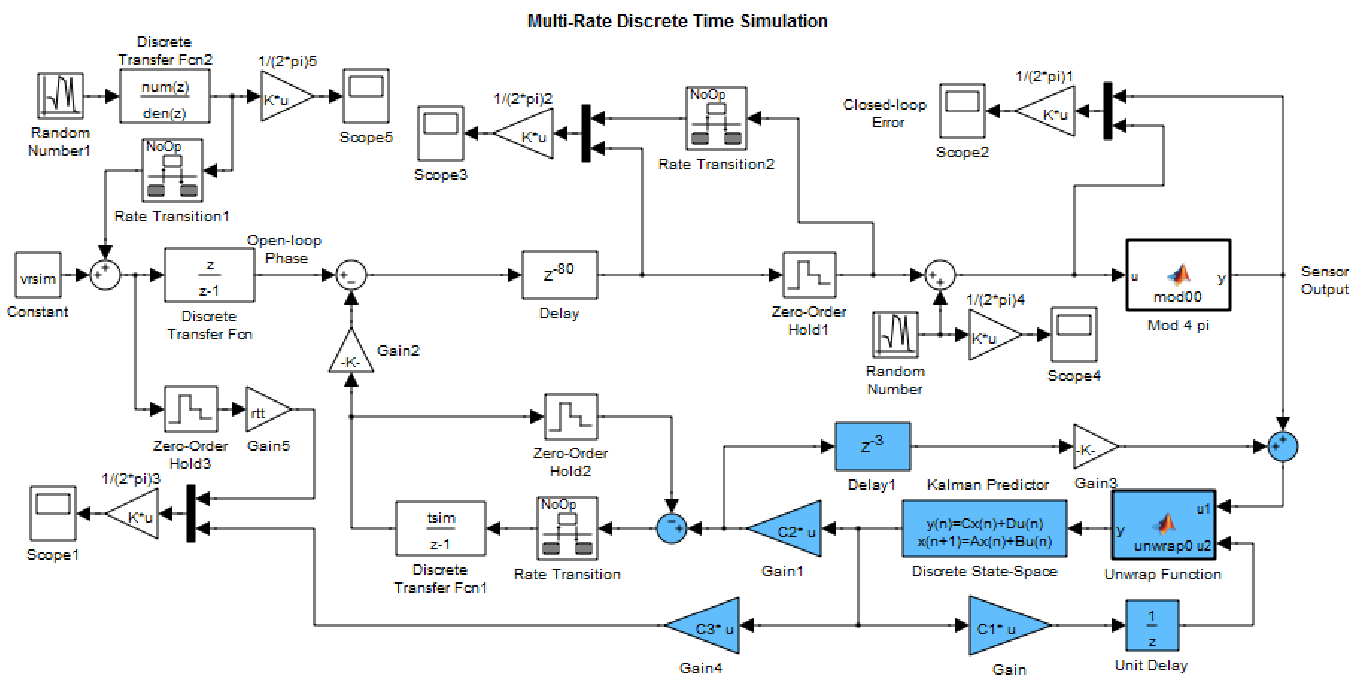

Figure 1. SIMULINK model for prediction and feedback control of a phase ramp. Mirror represented by integrator with sample time *tsim*. The model shown has a measurement delay equal to the length of two control sample intervals.

4.4 Effect of Sensor Noise and Velocity Variation on Closed-loop Error and Velocity Estimates

Figures 2 and 3 show, respectively, the closed-loop phase error and velocity estimate for $vr = 0.75\times 2\pi$ / control sample period (approximately the maximum velocity that this controller can track with reliable stability) and zero-mean white sensor noise. The measurement delay was two control sample periods and the sensor noise and velocity both had standard deviation = $0.1\times 2\pi$. (The standard deviation of the sensor noise equals the RMS value, since the noise has zero mean.) For Figures 4 and 5, the velocity had standard deviation = $0.1\times 2\pi$ but there was no sensor noise.

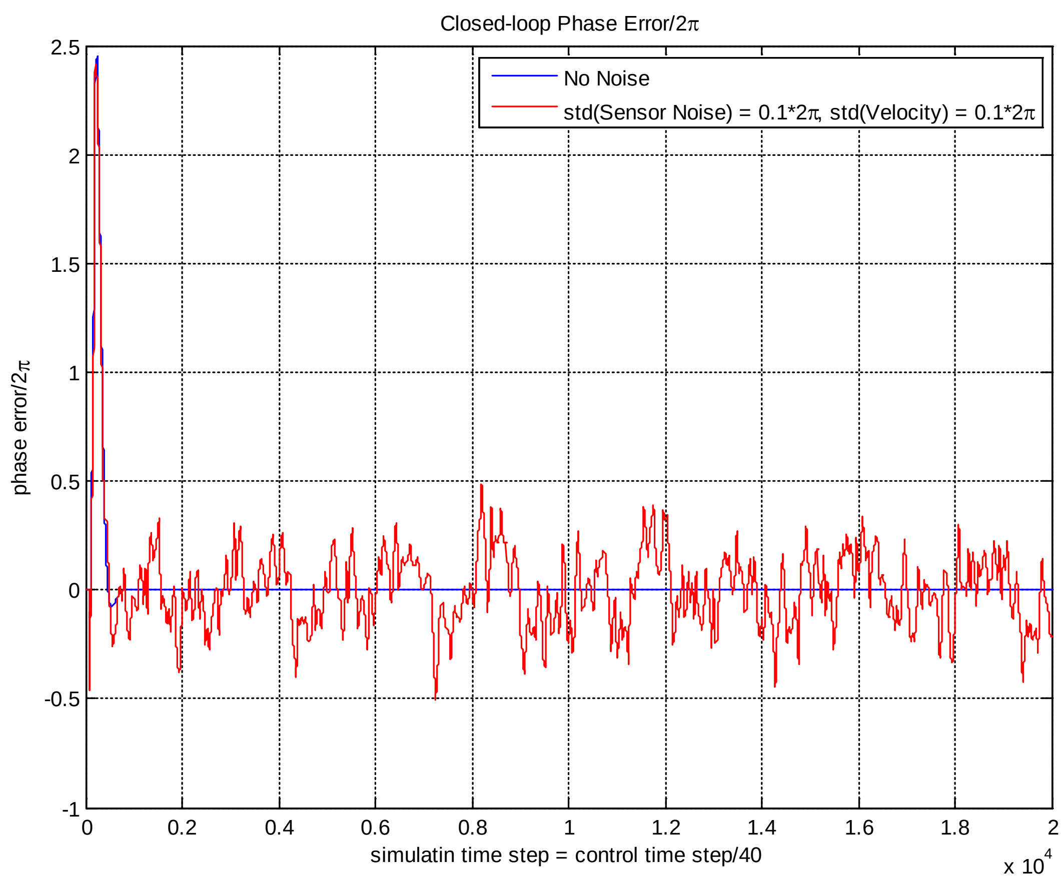

Figure 2. Closed-loop phase error / 2π. Measurement delay = 2 control sample intervals. Velocity $vr = 0.75\times 2\pi$ / control sample interval. Blue: constant velocity, no sensor noise. Red: velocity standard deviation = $0.1\times 2\pi$, sensor noise standard deviation = $0.1\times 2\pi$. Phase error sampled at the fast simulation rate.

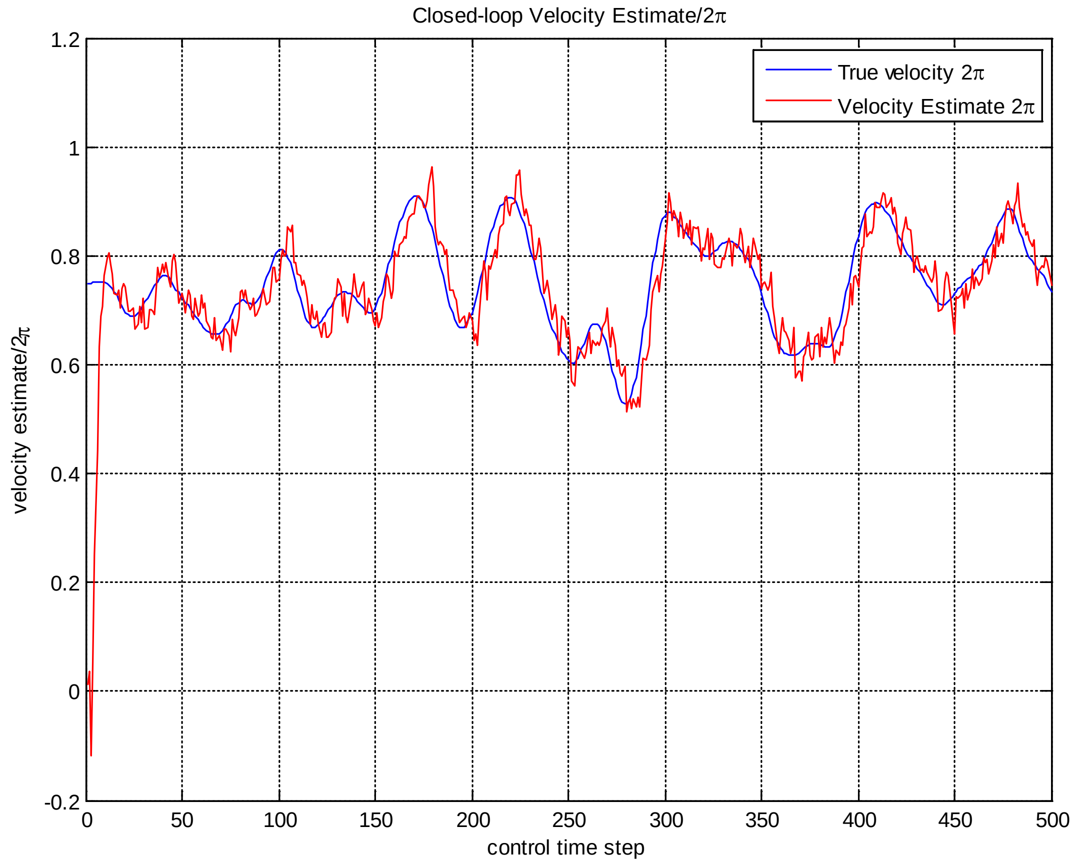

Figure 3. Closed-loop velocity estimate / 2π. Measurement delay = 2 control sample intervals. Velocity $vr = 0.75\times2\pi$ / control sample interval. Blue: constant velocity, no sensor noise. Red: velocity standard deviation = $0.1\times2\pi$, sensor noise standard deviation = $0.1\times2\pi$. Phase error sampled at the fast simulation rate.

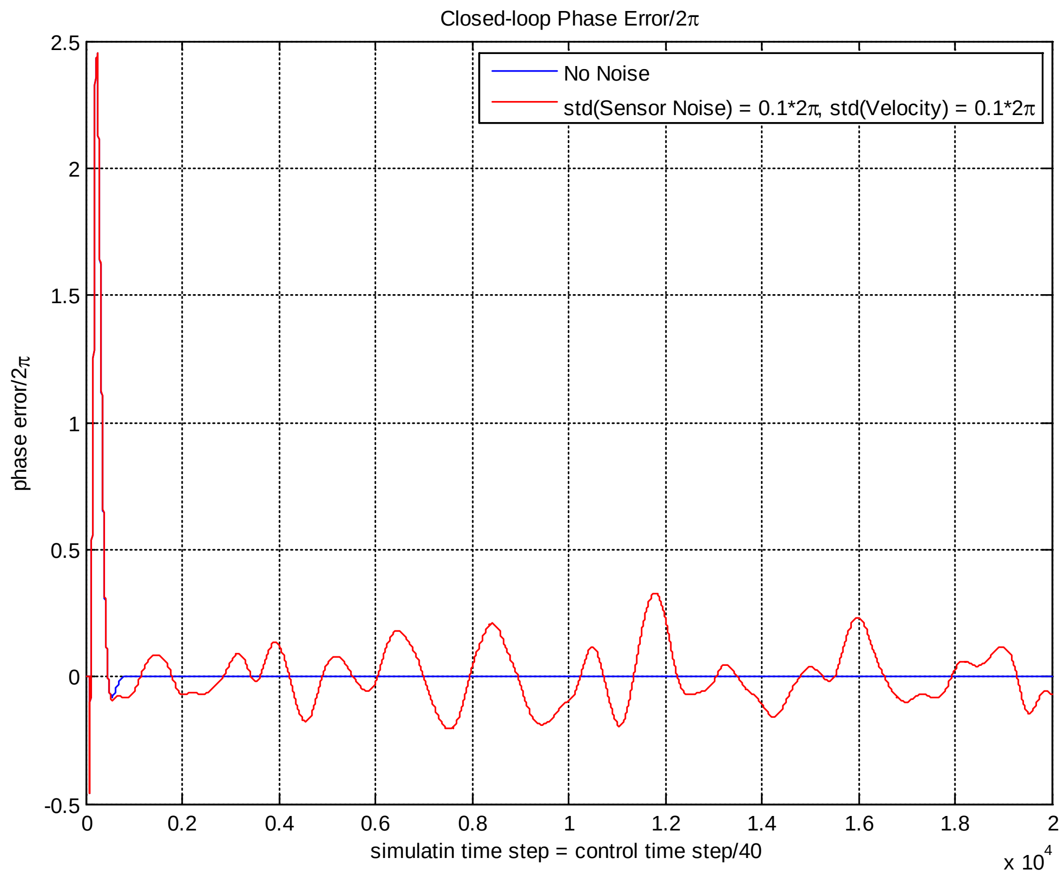

Figure 4. Closed-loop phase error / 2π. Measurement delay = 2 control sample intervals. Velocity *vr* = 0.75×2π / control sample interval. Blue: constant velocity, no sensor noise. Red: velocity standard deviation = 0.1×2π, no sensor noise. Phase error sampled at the fast simulation rate.

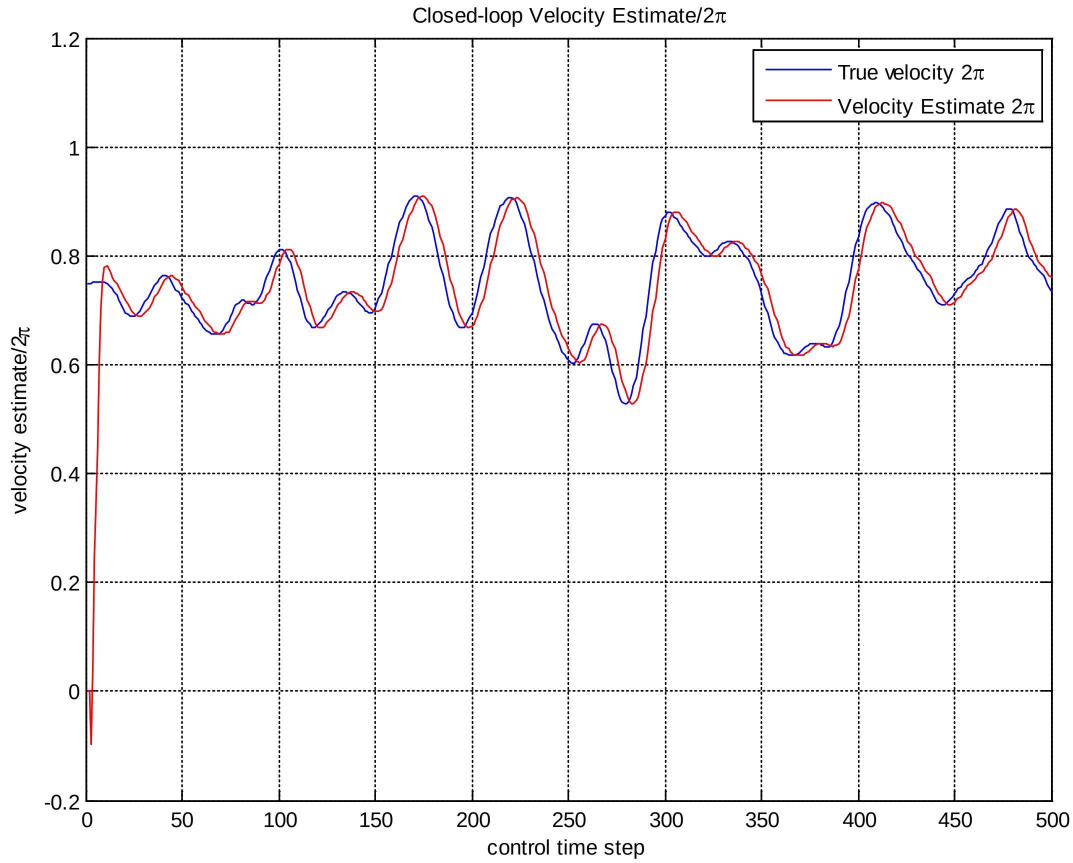

Figure 5. Closed-loop velocity estimate / 2π. Measurement delay = 2 control sample intervals. Velocity *vr* = 0.75×2π / control sample interval. Blue: constant velocity, no sensor noise. Red: velocity standard deviation = 0.1×2π, no sensor noise. Phase error sampled at the fast simulation rate.

5.0 CONCLUSIONS

This project has developed advanced methods for control, filtering, prediction and system identification in adaptive optics, laser beam pointing and target tracking. These methods can achieve significant improvements in on-target Strehl ratios and tracking jitter for phased-array high energy laser systems. The main technical contribution of the research under this grant is a method for phase unwrapping, prediction and correction in phased arrays. The new method combines phase unwrapping logic with Kalman filtering and prediction in a feedback control loop. Analysis and simulation have shown that the new method can track and correct optical phase with slowly varying phase velocity and that the method is reasonably robust to sensor noise. Further research should extend the methods developed here to multiple apertures and higher-order wavefront correction in phased-array systems.

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